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Long-term manure and cropping systems effect on soil water vapour sorption characteristics is controlled by soil texture

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ABSTRACT

Increasing studies indicate that long-term experiments (LTEs) involving manure application and optimal cropping systems can significantly improve soil physicochemical properties, which may also affect the soil water retention curve (WRC) in the wet region (pF < 4.2). However, few studies have explored the effect of long-term manure application and cropping systems on soil WRC in the dry region (water vapour sorption isotherms, WSIs) (pF > 4.2) as well as the associated soil physicochemical properties. To overcome this knowledge gap, we investigated the effect of long-term manure application (24 to 177 years) and different cropping systems (71 to 82 years) on soil organic carbon (SOC) content, WSIs, hysteresis, and specific surface area (SSA). Soil samples were collected from five long-term manure experiments in Sweden, the United Kingdom, Spain, Germany, and Denmark, and two long-term cropping systems experiments in the United Kingdom. The five manure LTEs comprised three soil textures (silty clay, silt loam, and sandy loam) with one to four crops grown in the fields, including wheat, barley, maize, and grass/clover. The cropping system LTEs comprised silt loam and sandy loam including bare fallow (BF), arable rotation, ley–arable rotation, and permanent grass. Results showed that long-term manure application increased SOC content in each site, but it had little effect on the soil WSIs, hysteresis, and SSA in silty clay soils. The changes of soil WSIs, hysteresis, and SSA in silt loam and sandy loam arising from manure application largely depend on the crops grown in the field. For the long-term cropping systems experiments, permanent grass had the most significant effect in increasing SOC content, soil WSIs in silt loam and sandy loam, and hysteresis and SSA in silt loam compared to other treatments. Compared to BF, arable rotation and ley-arable rotation had no effect on SOC and soil WSIs in silt loam, and on hysteresis and SSA in silt loam and sandy loam. Multiple linear regression models including SOC, clay, and silt contents sufficiently explained the variabilities observed in the soil WSIs, hysteresis, and SSA for both manure and cropping systems LTEs.

1. Introduction

Manure application and crop rotation are two common agricultural practices that reportedly improve soil physicochemical properties (Fu et al., 2022). However, changes in some soil physiochemical properties may require several years or even decades before significant effects are observed (Bai et al., 2018). Hence, long-term experiments (LTEs) serve as important platforms for evaluating the effect of agricultural practices on soil physiochemical properties (Rasmussen et al., 1998; Liu et al., 2020).

Several studies have demonstrated that long-term manure application improves soil organic matter (SOM) content (Blanco-Canqui et al., 2015; Triberti et al., 2016; Maillard et al., 2016). Meanwhile, other studies have shown that the enhancement of soil organic carbon (SOC) content influences other soil properties (Tisdall & Oades, 1982). For example, increasing SOC content may decrease soil bulk density (Yu et al., 2020), improve soil porosity and aggregation (Yagüe et al., 2016), cation exchange capacity (Ashworth et al., 2020), and nutrient cycling (Tiessen et al, 1994). Changes in some of these physiochemical properties are reported to have direct or indirect effects on soil water retention (Stoof et al., 2010). Therefore, it is important to evaluate the impact of manure application on SOC content and in turn, on soil water retention responses.

The changes in the SOC content under different cropping systems

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vary with the crop type in the sequence. For example, Liu et al. (2020) showed that legume crops-based rotation leads to higher SOC content than wheat monoculture. King and Blesh (2018) reported that soils with perennial and cover crops had higher SOC content than grain-only rotations, but cereal-legume grain rotations decreased SOC content. Other studies reported that perennial grasses maintain or increase SOC content compared to annual crops (Culman et al., 2010; Albers et al., 2020; Chen et al., 2022b). In addition to this, Albizua et al. (2015) and Chen et al. (2020b) reported that specific crop species and crop sequences in the cropping systems also affect SOC content. Therefore, a comprehensive assessment of how SOC content varies among different cropping systems and crop sequences is necessary for evaluating the changes in soil water retention.

The soil water retention curve (WRC) is a crucial soil property that reflects the ability of soil to provide water for plant growth, biological aspects, and other ecosystem services (e.g., buffering against flooding) (Robinson et al., 2019). The WRC can be partitioned into two: wet region (pF < 4.2; > -1.5 MPa) and dry region (pF > 4.2; < -1.5 MPa). The dry region of the WRC can be referred to as soil water vapour sorption isotherms (WSIs) (Arthur et al., 2014). The majority of studies that evaluate the effect of manure or cropping systems LTEs on the WRC have focused on its wet region. For example, Nyamangara et al. (2001) and Arriaga and Lowery (2003) found that long-term manure application significantly increased hydraulic properties in sandy soils and soil–water retention capacity in eroded soils. Fu et al. (2022) also indicated that long-term manure application treatments had significantly higher soil water content than no manure application treatments in clayey and silty loam soils, but the improvements in soil water content depended on the crops grown in sandy loam soils. In addition, for cropping systems, Rachman et al. (2004) showed that soil under perennial vegetation such as grass retained more water moisture than in the row crop corn area. Çerçioğlu et al. (2019) reported that cover crop inclusion in a crop rotation improved the hydraulic properties in clayey soils and significantly enhanced soil water retention after 5 years.

There are very limited studies on the long-term manure application or cropping systems' effect on the dry region water retention beyond the permanent wilting point (pF $= 4.2$). The dry region water retention, also known as water vapour sorption isotherms (WSIs), is important for characterizing and simulating water vapour transport, and volatilization of organic compounds during dry spells or in dry regions (Arthur et al., 2013) and knowledge of the effect of long-term management effects is needed. In a previous study, Zhou et al. (2020) reported that 33-year manure application did not affect soil water content at pF > 5.5 in Vertisol. Different soil textures may contain various clay mineralogy and content and SOC content, which may significantly affect soil WSIs (Arthur et al., 2014). However, few studies reported the effect of long-term manure or different cropping systems effects on the soil WSIs in different soil textures.

Soil WSIs exhibit hysteresis between adsorption and desorption of the sorption isotherm (Prunty & Bell, 2007; Arthur et al., 2013 & Arthur et al., 2015a; Arthur et al., 2015b). This hysteresis also affects the processes of soil evaporation and water vapour flow abilities in dry regions (Bittelli et al., 2008; Arthur et al., 2013). Usually, the soil WSIs and hysteresis are also linked to soil clay content and specific surface area (SSA) (Chen et al., 2022a). Thus, knowledge about these soil physicochemical properties is important to understanding the soil water sorption characteristics and water vapour flow in dry regions. Based on experimental data from soil samples taken from five long-term manure applications and two long-term cropping systems in five European countries, we aimed to (1) investigate how long-term manure and cropping systems affect WSIs characteristics of different soil textures; (2) explore the interaction between crop type and manure on WSIs characteristics; (3) explain variations in WSIs characteristics of LTEs based on soil texture and SOC content.

2. Methodology

2.1. Field site and sampling

2.1.1. Long-term manure sites

The study utilized five long-term manure experimental field sites (LTEs) (Fig. 1a), which had contrasting soil textures and crop types in rotation. In the first three sites (below), we collected the soil samples under wheat plots, but in the other two sites, we collected the soil samples under different crop types. The sites listed below follow the descending order of clay content.

The Lanna manure LTE started in 1996 at the Lanna agriculture research station in Sweden (denoted SEL) (58°21′N, 13°08′E, 75 m above mean sea level). The average annual temperature is 7.3 °C and the average annual rainfall is 636 mm (Kätterer et al., 2014). The soil is silty clay (Fig. 1b), classified as Auqic Haplocryept (Soil Survey Staff, 1999), and the clay mineralogy is characterised by mica/illite and traces of kaolinite (Eriksson et al., 2016). The crop rotation consisted of oat (10 years), spring barley (4 years), spring wheat (1 year), and winter wheat (3 years) were grown between 2002 and 2019. Thus, the field had winter wheat at the time of sampling. The two treatments considered were an unfertilized arable field (UNF) and the manured (MN) treatments. The MN treatment was done by adding 38 t ha^{-1} of farmyard manure (fresh cattle manure with straw bedding containing approximately 4 t ha^{-1}C) every two years before ploughing (Kätterer et al., 2014). Each treatment had four replicates, and the area of each plot was 112 m^2 (8 m wide and 14 m long).

The Broadbalk manure LTE started in 1843 at Broadbalk in the United Kingdom (denoted UKB) (51°49′N, 0°22′W, 125 m above mean sea level). The average annual temperature is 9.8 °C and the average annual rainfall is 733 mm (Macholdt et al., 2020). The soil is silt loam (Fig. 1b), classified as an Auqic or Typic Paleudalf (Soil Survey Staff, 1999), and the clay mineralogy is dominated by smectite, kaolinite and subsidiary mica (Blake et al., 1999). The crop rotation consists of beans, wheat, wheat, oat and wheat since 2019, before which forage maize and potatoes were in the sequence. The 4.8-ha field is divided into 20 strips and 10 sections, and the size of each plot is 138 m^2 (6 m wide and 23 m long). The two treatments were UNF (strip 3, section 2) and MN which comprised 35 t ha^{-1} year^{-1} farmyard manure (fresh cattle manure) (MN) (strip 2, section 2). The added 35 t ha^{-1} farmyard manure contained about 3 t ha^{-1}C (Macholdt et al., 2020).

The La Higueruela manure LTE started in 1985 at the La Higueruela experimental field station in Spain (denoted ESL) (40°03′N, 04°24′W, 450 m above mean sea level). The average annual temperature is 15.5 °C and the average annual rainfall is 468 mm (Kautz et al., 2006). The soil is sandy loam or a sandy clay loam (Fig. 1b), classified as a Calcic Haploxeralf (Soil Survey Staff, 1999), and the clay fraction is characterised by 57% illite, 19% smectite and traces of kaolinite (Plaza et al., 2013). The crop rotation consists of sorghum, spring barley, and winter wheat. Two treatments which were UNF and 30 t ha^{-1} 3 years^{-1} farmyard manure (2-year old cattle manure containing 9.6 t ha^{-1}C) arable field (MN) were selected (Kautz et al., 2006). Each treatment had three replicate plots measuring 6 m wide and 8 m long.

The Bad Lauchstädt manure LTE started in 1902 at the UFZ Research Station Bad Lauchstädt in Germany (denoted DEB) (51°24′N, 11°53′E, 121 m above mean sea level). The average annual temperature is 8.7 °C and the average annual rainfall is 484 mm (Merbach & Schulz, 2013). The soil is silt loam (Fig. 1b), classified as a Typic Mollisol (Soil Survey Staff, 1999) and the clay fraction is dominated by illite with some kaolinite (Séquaris et al. 2010). The crop rotation consisted of spring barley, maize, and wheat. Both crops are grown in parallel fields so that they are permanently present in the experiment. The two treatments which were UNF and 30 t ha^{-1} 2 years^{-1} farmyard manure (cattle barn containing 5 t ha^{-1}C) arable field (MN) were selected (Merbach & Schulz 2013). The LTE has no field replicate plots as each treatment plot was 10 m wide and 27 m long.

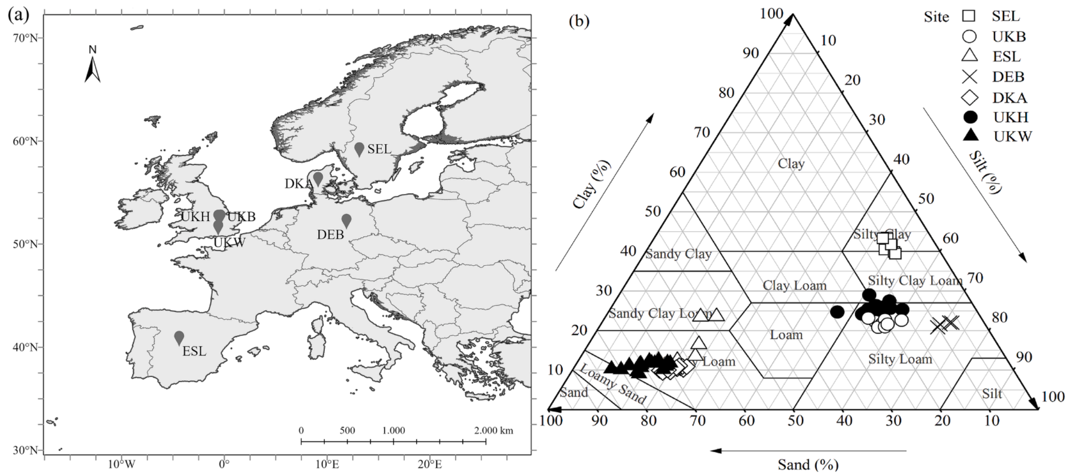

Fig. 1. (a) Location of the investigated samples in the seven field sites. (b) The distribution of the investigated samples in the seven field sites displayed on the USDA soil textural triangle. SEL, Lanna; UKB, Broadbalk; ESL, La Higueruela; DEB, Bad Lauchstädt; DKA, Askov; UKH, Highfield; UKW, Woburn.

The Askov manure LTE started in 1894 at the Askov research station in Denmark (denoted DKA) (55°28′N, 09°07′E, 56 m above mean sea level). The average annual temperature is 7.7 °C and the average annual rainfall is 869 mm (Jensen et al., 2016). The soil texture is sandy loam (Fig. 1b), classified as a Typic Hapludalf (Soil Survey Staff, 1999) and the clay mineralogy is primarily illite, smectite and kaolinite (Barré et al., 2010). The crop rotation consisted of winter wheat, silage maize, spring barley, and grass/clover mixture. All the crops are grown in parallel fields so that they are permanently present in the experiment. The treatments considered for this work were UNF and 37.5 t ha^{-1} yr^{-1} farmyard manure (cattle slurry containing 0.8 t ha^{-1}C) arable field (MN) in the four different fields (Jensen et al., 2022). The manure of the MN treatments was added in March or April to the surface of wheat plots, and before ploughing for maize and barley plots. The grass was undersown with barley and when the barley was harvested, the grass/clover mixture was left in the field as a rotation element until August of the following year. Each treatment had three replicate plots, and the area of each plot of winter wheat was 63 m^2 (7 m wide and 9 m long), and silage maize, spring barley, and grass/clover mixture plots were 108 m^2 (12 m wide and 9 m long) each.

Soil sampling took place from July through August 2020 for the SEL, DEB and DKA sites, and from July through August 2021 for the UKB and ESL sites. The soil samples were collected under wheat in SEL, UKB, and ESL, under barley and maize in DEB, and under wheat, silage maize, barley, and grass/clover in DKA, respectively. All the soil samples were extracted at a depth of 5 – 15 cm and stored in a 2 °C room until further analyses.

2.1.2. *Long-term cropping systems field site and sampling*

In addition to the five manure LTEs, we included two cropping systems LTEs (Highfield and Woburn) from Rothamsted Research in the United Kingdom (Fig. 1a), which had contrasting soil textures. Sampling for the two sites was carried out in August 2021.

The Highfield cropping systems LTE started in 1949 and is denoted UKH (51°48′N, 00°36′W, 127 m above mean sea level). The average annual temperature is 10.2 °C and the average annual rainfall is 718 mm (Scott et al., 2014). The soil is a silt loam (Fig. 1b), classified as an Aquic Paludalf (Soil Survey Staff, 1999), and the clay mineralogy is dominated by smectite, kaolinite and subsidiary mica (Blake et al., 1999). We selected five treatments from this site: (1) BF: continued bare fallow, but regular tillage maintained free of plants; (2) wheat (arable) (WA): arable crops rotation consists of winter wheat (3-year), fallow (1 year) and winter oats (1 year) fertilized with 220 kg N ha^{-1} year^{-1}, 65 kg P ha^{-1} 3 years^{-1} and 250 kg K ha^{-1} 3 years^{-1}; (3) wheat (ley – arable) (WLA) and (4) ley (ley – arable) (LLA): 6 years rotation with 3 years grass/clover ley followed by 3 years wheat. The grass/clover ley had no N fertilizer but was fertilized with 65 kg P ha^{-1} 3 years^{-1} and 250 kg K ha^{-1} 3 years^{-1}. The last treatment was grass: permanent grassland which was established in 1949, and the grass was managed the same as ley (Jensen et al., 2019). Each treatment had four replicates, and the area of each plot of WLA and LLA was 350 m^2 (7 m wide and 50 m long), and the other plots were 60 m^2 (6 m wide and 10 m long).

The Woburn cropping systems LTE started in 1938 and is located in Husborne Crawley, Bedford and denoted as UKW) (51°59′N 0°37′W, 99 m above mean sea level). The average annual temperature is 9.4 °C and the average annual rainfall is 640 mm (Johnston et al., 2017). The soil texture is sandy loam (Fig. 1b), classified as a Quartzipsammetric Haplumbrept (Soil Survey Staff, 1999) and the dominant clay mineral is vermiculite (Jenkinson, 1977). We selected five treatments from this site: (1) BF: continuous bare fallow; (2) wheat (arable) (WA): rye beans, oats and two test crops: wheat and rye; (3) wheat (ley – arable) (WLA) and (4) ley (ley – arable) (LLA): 3 years grass/clover ley followed by 1-year wheat, 1-year rye. (5) permanent grass. Fertilizers, lime, and pest control were applied according to standard farm practice (Johnston et al., 2017). Each block has eight pairs of plots, and each plot was 180 m^2 (9 m wide and 20 m long).

The difference between WLA and LLA was the standing crop during sampling. The soil sampling time of WLA and LLA was the wheat growth period and grass/clover ley growth period, respectively. All soil samples were taken from a depth of 5 – 15 cm and stored in a 2 °C room until further analyses.

2.2. *Laboratory measurements*

2.2.1. *Soil texture and organic carbon*

The samples were air-dried, crushed, and passed through a 2 mm sieve. The soil texture of the soil samples was analyzed by combined hydrometer and wet sieving methods (Gee & Or, 2002). SOC content was determined on milled subsamples by dry combustion using a Vario MAX cube (Elementar Analysensysteme AG, Langenselbold, Germany).

2.2.2. *Soil water vapour sorption isotherm*

Soil WSIs were determined with an automated vapour sorption analyzer (METER Group Inc., Pullman, WA, USA) on samples that were air-dried to a stable relative humidity (*RH*) of 45%. The isotherms covered an *RH* range from 3% to 93% with a measurement resolution and temperature of 2% *RH* and 25℃, respectively. After the measurements, the samples were oven-dried for 48 h to determine the water contents at the respective *RH* values. Full details about the measurement methodology can be found in Arthur et al. (2014).

2.2.3. Hysteresis and specific surface area

Hysteresis (*Hys*) of the soil WSIs were computed for the adsorption–desorption data between 10 and 80% *RH* by summing up the difference in hygroscopic water content (w_h) between adsorption (w_a) and desorption (w_d) as described in Equation (1) (Arthur et al. 2020):

$$Hys = \left[\left(\sum_{i=80}^{i=10} w_d - w_a\right) \Big/ n\right] \times 100 \quad (1)$$

where n is the number of data points ($n = 36$).

Soil specific surface area (SSA) was estimated by parameterizing the Tuller-Or model (Tuller & Or, 2005) model with the water vapour desorption data. The TO model relates the equilibrium soil water content, w (kg kg^{-1}) to matric potential ψ (m H_2O) and SSA (m^2 kg^{-1}) as:

$$w = \sqrt[3]{\frac{A_{svl}}{6 \times \pi \times \rho_w \times g \times \psi}} SA \quad (2)$$

where A_{svl} (J) denotes the Hamaker constant for solid–vapor interactions through the intervening liquid, set to -6×10^{-20} J as reported by Tuller and Or (2005) and Maček et al. (2013), ρ_w is the density of water (1000 kg m^{-3}) and g is the acceleration due to gravity (9.8 m s^{-2}).

The model was parameterized with the sorption data (adsorption and desorption separately) by employing the Levenberg-Marquardt nonlinear least-squares algorithm implemented in the "*minpack.lm*" package (Elzhov et al., 2016) in R v4.0.2 (R Core Team, 2020).

2.3. Data analysis

Excel 2010 was used for data compilation and analysis. SPSS Statistics 18.0 (SPSS Inc. Chicago, IL, USA) was used for statistical analysis, and Origin 2021 was used to create the figures. Before statistical analysis, we first assessed the normality (Shapiro-Wilk test) and constant variance (Brown-Forsythe test) of the data. The statistical significance of the difference between the UNF and MN treatments for each manure LTE was tested by the Student's *t*-test ($P < 0.05$). Statistical comparison of the treatments in the crop rotation LTE was done using One-way ANOVA followed by Tukey's HSD test for mean separation. Due to the lack of field replicates at the DEB site, the site was excluded from the statistical tests. The clay content of the ESL site ranged from 11 to 23%, and it is known that clay content is linearly correlated to water vapour sorption (Schneider and Goss, 2012; Arthur et al., 2015a; Arthur et al., 2015b). Consequently, the analysis of manure effect on soil WSIs characteristics for the ESL site was conducted using One-way analyses of covariance (ANCOVA) with clay content as the covariate. The measured and derived water vapour sorption variables were adjusted to the average clay content of the manure dataset (17%). Considering the correlation between soil properties and water vapour sorption variables, we selected SOC, clay, and silt content for building multiple linear regression models of soil WSIs, hysteresis, and SSA.

3. Results

3.1. Soil organic carbon

Compared to the UNF treatments across the LTEs, long-term manure application significantly increased SOC content by 19% – 265%, and this positive effect was consistent regardless of the prevailing crop or soil texture (Table 1). The largest increase (265%) was at the silt loam UKB site while the smallest increase occurred at the silty clay SEL site. Considering the DKA site, there was no effect of crop type on the SOC increase after manure addition.

For the cropping systems LTEs, the SOC content at the silt loam UKH site was in the order BF < WA < WLA < LLA < Grass, with a similar trend for the sandy loam UKW site except for similar SOC contents for the WLA and LLA site. The grass treatments had the most significant effect in increasing SOC content compared to other treatments, which increased by 171% in silty loam UKH and 287% in sandy loam UKW sites, respectively (Table 2).

Table 1
Soil organic carbon content (%) of samples from the five long-term manure application field sites.

Site (soil texture)	Crop	UNF	MN
SEL (SiC)	Wheat	1.93 ± 0.02b	2.30 ± 0.06a
UKB (SiL)		0.75 ± 0.02b	2.74 ± 0.08a
ESL (SL)		0.58 ± 0.03b	0.93 ± 0.09a
DEB (SiL)	Maize	1.64	2.23
	Barley	1.57	2.32
DKA (SL)	Wheat	1.13 ± 0.02b	1.54 ± 0.10a
	Maize	1.10 ± 0.08b	1.48 ± 0.10a
	Barley	1.06 ± 0.03b	1.35 ± 0.05a
	Grass	1.19 ± 0.04b	1.63 ± 0.01a

Data reported as mean ± standard error (SE). The lowercase letters in the same row indicate a significant difference ($P < 0.05$) between treatments. For the DEB site, the SE of replicates within one plot, so the data were excluded from the *t*-test. UNF, unfertilized arable field; MN, manure arable field; SEL, Lanna; UKB, Broadbalk; ESL, La Higueruela; DEB, Bad Lauchstädt; DKA; Askov; SiC, silty clay; SiL, silt loam; SL, sandy loam.

3.2. Soil water vapour sorption isotherm

To evaluate the effect of manure and cropping systems on the WSIs, we used the isotherm curves and the total water sorbed for the RH range considered. Despite the large increases in SOC, there was no significant difference in soil desorption WSIs between the UNF and MN treatments at the silty clay SEL, sandy loam ESL, and sandy loam DKA maize and barley sites (Fig. 2). However, the MN treatment at the silt loam soils (UKB, DEB-barley) had larger soil WSIs relative to the UNF treatment (Fig. 2b & d). For the sandy loam DKA site, there was a strong effect of the prevailing crop on the soil WSIs. Manure application increased soil WSIs significantly under the wheat crop (Fig. 2f), increased under the grass crop (Fig. 2i), but did not affect the soil WSIs under the maize (Fig. 2g) and barley crops (Fig. 2h).

Regarding the cropping systems LTEs, there was little difference in soil WSIs of the BF, LLA, WLA, and WA treatments of the silt loam UKH site, while the grass treatment had significantly higher soil WSIs than the BF treatment (Fig. 3a). In the silt loam UKH site, all the treatments exhibited larger soil WSIs than the BF treatment at higher *RH* levels (>50%) (Fig. 3b), but the total water sorbed was not significantly different among the treatments.

3.3. Hysteresis

Across all LTEs with manure treatments, there was a general trend of increased hysteresis on the manure treatments. The significance of this increase, however, depended on soil texture and crop type. For example, there was no significant difference in hysteresis between UNF and MN

Table 2
Soil organic carbon content (%) of samples from the two long-term crop rotation field sites.

Crop	UKH (SiL)	UKW (SL)
BF	1.51 ± 0.06b	0.39 ± 0.05c
WA	1.64 ± 0.06b	0.86 ± 0.03b
WLA	1.80 ± 0.05b	1.02 ± 0.05b
LLA	2.03 ± 0.17b	0.97 ± 0.04b
Grass	4.09 ± 0.26a	1.51 ± 0.10a

Data reported as mean ± standard error (SE). The lowercase letters in the same column indicate a significant difference ($P < 0.05$) among treatments. BF, bare fallow, WA, wheat (arable); WLA, wheat (ley – arable); LLA, ley (ley – arable); UKH; Highfield; UKW; Woburn; SiL, silt loam; SL, sandy loam.

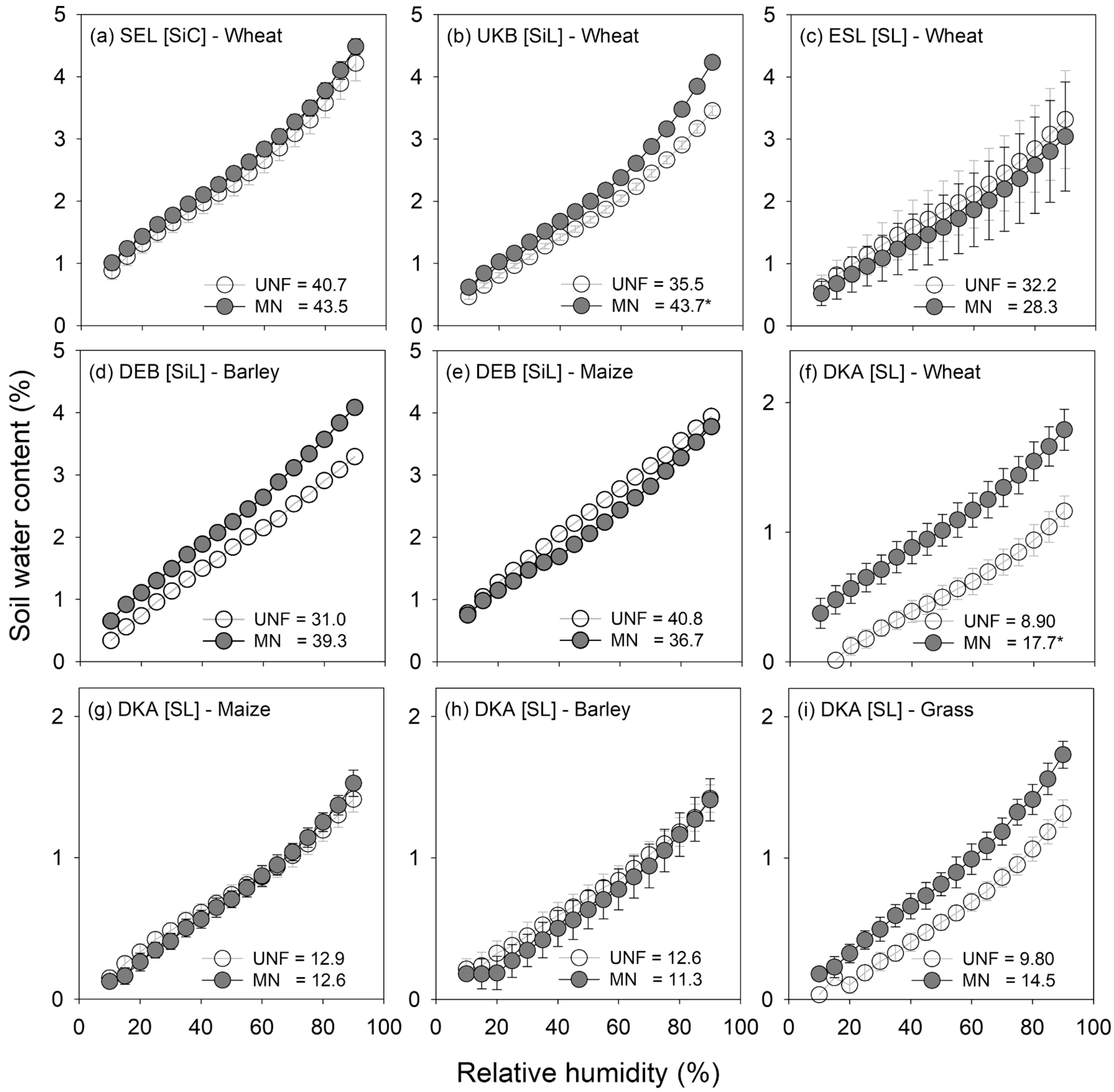

Fig. 2. Soil water vapor desorption isotherms of samples from the five long-term manure field sites and different crops. The error bars represent the standard error (SE) of the mean. UNF, unfertilized arable field; MN, manure arable field; SEL, Lanna; UKB, Broadbalk; ESL, La Higueruela; DEB, Bad Lauchstädt; DKA, Askov. SiC, silty clay; SiL, silt loam; SL, sandy loam. Numbers in the legend represent the total amount of sorbed water (%); An asterisk indicates a significant difference between the manure and unfertilized treatments.

treatments at the silty clay SEL under wheat (Fig. 4a), and the sandy loam DKA under maize and grass (Fig. 4b). However, manure application significantly increased hysteresis in the silt loam UKB and sandy loam ESL under wheat (Fig. 4a), and in the sandy loam DKA under wheat and barley (Fig. 4b). Although the DEB site data was not statistically evaluated, the trend of increased hysteresis after manure application was also observed.

In the cropping systems LTEs, the grass treatment had significantly larger hysteresis than other treatments, and the hysteresis of WLA was significantly lower than that of WA in the silt loam UKH site (Fig. 4c). However, cropping systems had no significant effect on hysteresis at the sandy loam UKW site (Fig. 4c).

3.4. Soil specific surface area (SSA)

Across all LTEs, there was a general trend of increased SSA after manure application. The significance of this increase also depended on soil texture and crop type. For example, there was no significant difference in SSA between UNF and MN treatments at the silty clay SEL and sandy loam ESL under wheat (Fig. 5a), and the sandy loam DKA under maize and barley (Fig. 5b). However, manure application significantly increased SSA in the silt loam UKB under wheat (Fig. 5a), and in the sandy loam DKA under wheat and grass (Fig. 5b). For the silt loam DEB site, the trend of increased SSA under barley plot after manure application was also observed.

In the cropping systems LTEs, the grass treatment had significantly larger SSA than BF, WLA, and LLA, and no significant difference in SSA was observed among BF, WA, WLA, and LLA in the sandy loam UKH site (Fig. 5c). The cropping systems had no significant effect on SSA at the silt loam UKW site (Fig. 5c).

3.5. Relations between SOC, hysteresis, SSA, and soil water vapour sorption.

The relationship between SOC, clay and silt contents, and soil WSIs (e.g., RH_{50}), hysteresis, and SSA could be accurately described with multiple linear regression across all LTEs ($P < 0.001$). In general, higher SOC, clay, and silt contents were linked to higher soil WSIs, hysteresis, and SSA in soils (Fig. 6).

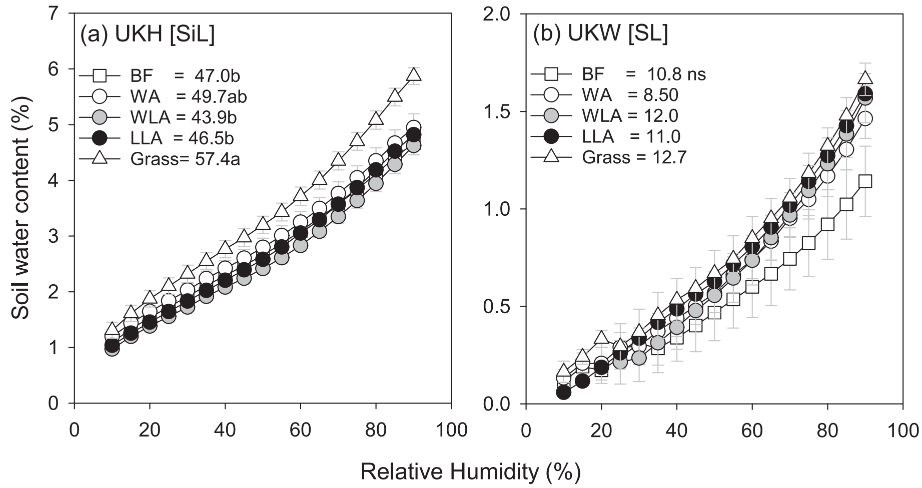

Fig. 3. Soil water vapor desorption isotherms of samples from the two long-term crop rotation field sites. BF, bare fallowed, WA, wheat (arable); WLA, wheat (ley – arable); LLA, ley (ley – arable); UKH; Highfield; UKW; Woburn; SiL, silt loam; SL, sandy loam. Note: the data points for BF and LLA overlap each other in (a). Numbers in the legend represent the total amount of sorbed water (%); Different letters after the number indicate a significant difference among treatments.

4. Discussion

Very few studies have investigated the effect of soil management practices (organic amendments or cropping systems) on the dry region of the water retention curve (WSIs), and the limited studies available only utilized data from one field site (e.g., Arthur et al., 2015a; Arthur et al., 2015b; Zhou et al., 2020). The novelty of this study is the evaluation of the manure and cropping systems' effect on WSI in seven LTEs under different edaphic and climatic conditions.

4.1. Effect of long-term manure application on WSIs

Our results showed that long-term manure application significantly increased SOC content regardless of soil texture and crop type. In this study, the average C added per year to the LTEs ranged from 0.8 t C ha^{-1} in the DKA to 3.2 t C ha^{-1} in the ESL field. Thus, this observed increase directly results from the high amount of C added to the field through the manure application. This has been documented in several studies for different kinds of manures (e.g., Sommerfeldt et al., 1988; Gerzabek et al., 1997; Lin et al., 2019; Zhou et al., 2020).

The effect of long-term manure application on soil WSIs varied depending on soil texture and crop type (Fig. 2a, b). The clay mineralogy of the manure LTEs was primarily dominated by illite/mica clay minerals, except UKB which had a mixture of mica, smectite and kaolinite. Consequently, the role of clay mineralogy across the different LTEs is expected to be minimal. The variation in clay content among the sites is much larger (10 to 45%) and significantly influenced how the manure addition affected the WSIs. For example, the non-significant effect of manure on the silty clay SEL site is likely due to the high clay and silt contents. The relatively higher surface area of the illite clay particles may be blocked by the low-surface SOC particles (Arthur et al., 2023), resulting in a small net effect on water sorption. For samples that contained appreciable amounts of illite or montmorillonite, the removal of organic matter from soil samples led to increased water sorption and surface area (Feller et al., 1992; Arthur et al., 2023). This was attributed to the removal of the organic coatings from the clay particles, and the further division of the clay particles that were initially bound together by organic matter. Another reason for the lack of an effect of manure on WSI at SEL may be the originally high SOC content of the soil (1.93%),. This is supported by other studies, which showed that the net effects on soil WSIs largely depend on their initial SOC content (Arthur et al., 2020; Chen et al., 2014 & 2022a). Meanwhile, the high clay content in the silty clay SEL site can help to stabilize SOM and limit its decomposition (Six et al., 2002), which makes the soil WSIs less sensitive to changes in SOC content (Rawls et al., 2003).

Furthermore, the soil WSIs in half of the fields in the sandy loam DKA site were much more sensitive to long-term manure application as compared with silt loam UKB and DEB and silty clay SEL sites. These results concur with the experiment of Rawls et al. (2003), who found that the sensitivity of water retention characteristics to changes in SOC content in lower clay content was higher than that of higher clay content. This is because an increase in SOC leads to larger SSA (Pennell et al., 1995), especially for coarse-textured soils, which have a positive contribution to soil WSIs at small saturations and in the absence of water repellency (de Jonge et al., 2000). There was no observed water repellency in the samples because the clay plus silt contents were>10% in almost all the samples. For such samples, the adsorptive forces of the fine clay and silt particles easily overcome the hydrophobic tendencies of the organic matter due to the relatively low SOC content (>5%) (Arthur et al., 2023).

Finally, The characteristics of the organic matter from the prevailing crop input can interact with the soil texture to affect the WSIs. For the same soil type (DEB), the tendency of higher water sorption for the barley plots compared to maize, despite similar increases in SOC from manure, may be attributed to the quality of SOC. For samples taken from wheat, there was a tendency for increased SSA regardless of soil texture (Fig. 5), while maize plots did not affect the WSIs or SSA. The high SOC input from the grass was the reason for the higher WSI and SSA for the manure compared to the control. Studies showed that increased SOC can contribute positively to soil WSIs (Arthur et al., 2018; Chen et al., 2022a), particularly in soils that have low clay contents such as the DKA site. Altogether, our findings underline that the change of soil WSIs from long-term manure application depends on the soil texture and crop types, however, caution is required when comparing and interpreting these results for other soil textures and crop types.

The hysteresis of soil WSIs can be attributed to the difference between the energy required during the water adsorption and desorption processes (Lu & Khorshidi, 2015). Long-term manure application did not significantly affect hysteresis in the silty clay SEL site, which was similar to the phenomenon of soil WSIs (Fig. 3a). The high clay and high initial SOC contents may have masked the effect of manure application on the differences between the heat of evaporation (desorption) and the heat of liquefaction (adsorption) (Chen et al., 2022a). Thus, the hysteresis values did not differ greatly after long-term manure application in the silt clay SEL site. In addition, we found that long-term manure application increased hysteresis in the silt loam UKB and DEB, and sandy

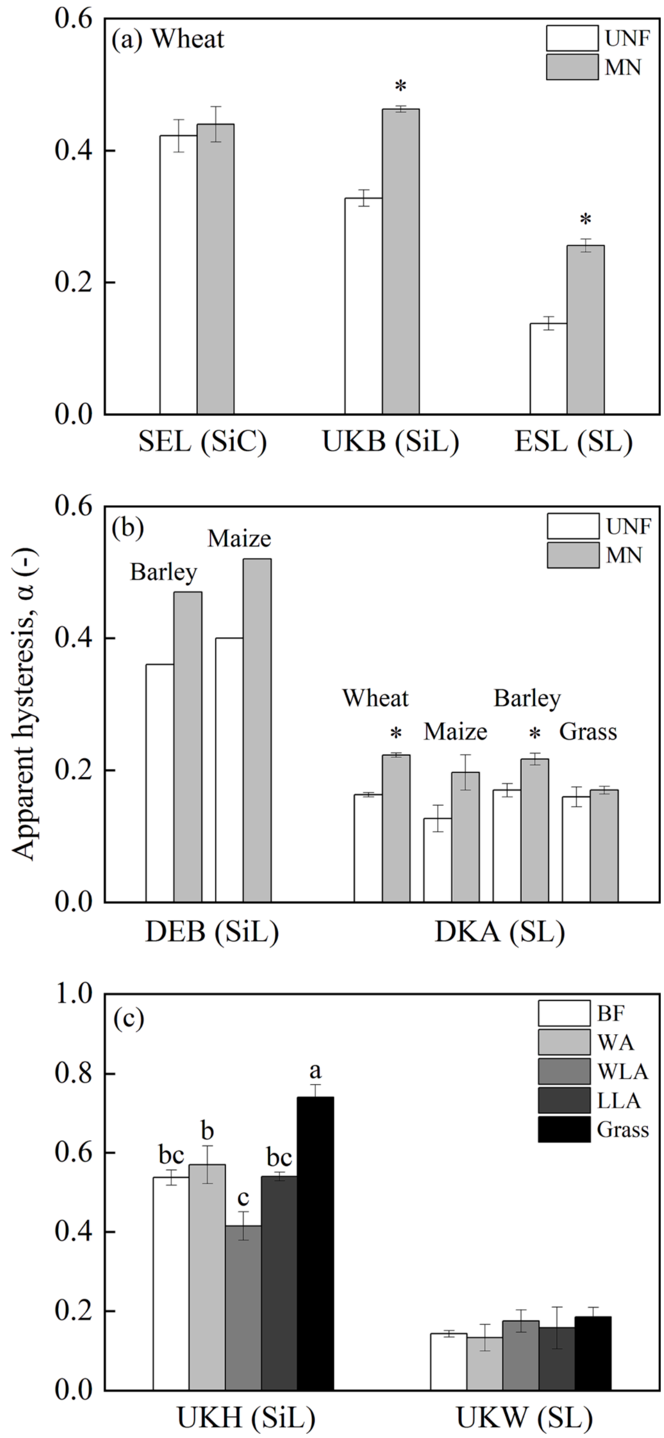

Fig. 4. Apparent hysteresis of samples from the seven field sites. Asterisks (*) and lowercase letters indicate the significant difference between treatments ($P < 0.05$). The bars without letters or * indicate no significant difference between treatments ($P > 0.05$). The error bars represent the standard error (SE) of the mean. For the DEB site, error bars represent the SE of replicates within one plot, so the data were excluded from statistical analysis. For the ESL site, clay content varies greatly between the treatments, so the data were analyzed by ANCOVA analysis. UNF, unfertilized arable field; MN, manure arable field; BF, bare fallowed, WA, wheat (arable); WLA, wheat (ley – arable); LLA, ley (ley – arable); SEL, Lanna; UKB, Broadbalk; ESL, La Higueruela; DEB, Bad Lauchstädt; DKA, Askov; UKH, Highfield; UKW, Woburn; SiC, silty clay; SiL, silt loam; SL, sandy loam.

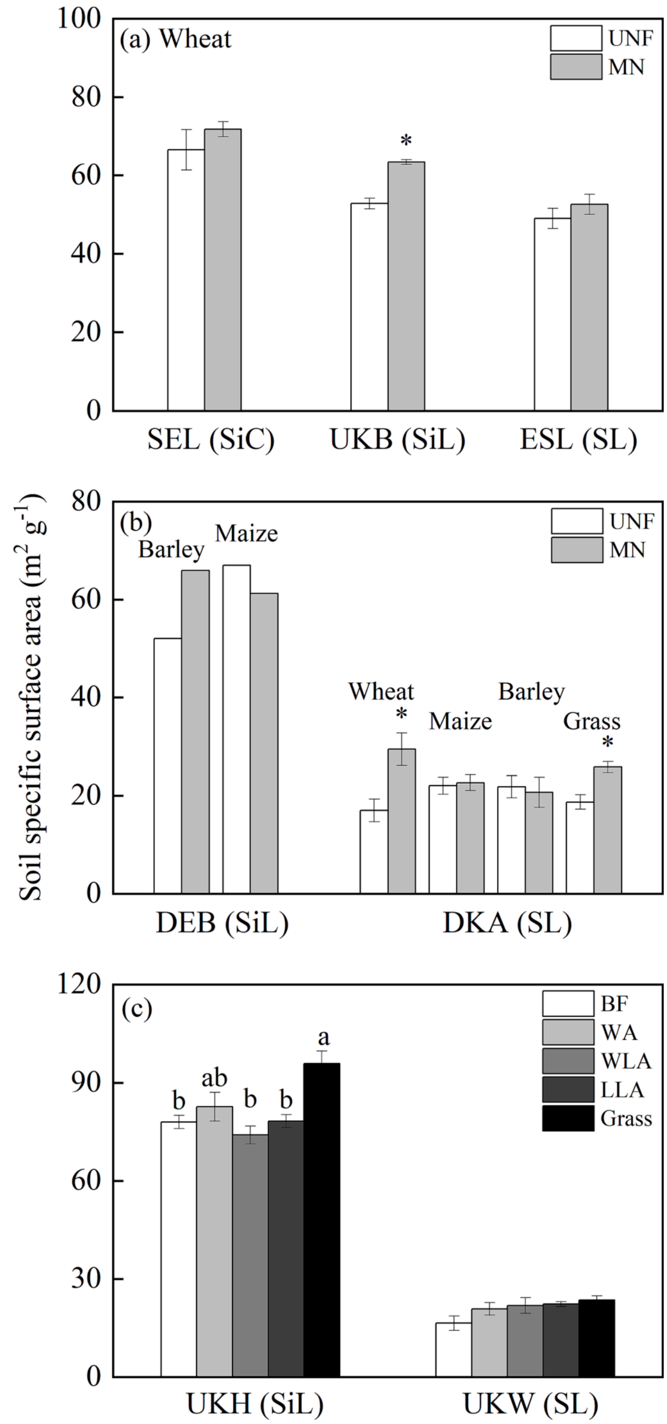

Fig. 5. Soil specific surface area of samples from the seven field sites. Asterisks (*) and lowercase letters indicate the significant difference between treatments ($P < 0.05$). The bars without letters or * indicate no significant difference between treatments ($P > 0.05$). The error bars represent the standard error (SE) of the mean. For the DEB site, error bars represent the SE of replicates within one plot, so the data were excluded from statistical analysis. For the ESL site, clay content varies greatly between the treatments, so the data were analyzed by ANCOVA analysis. UNF, unfertilized arable field; MN, manure arable field; BF, bare fallowed, WA, wheat (arable); WLA, wheat (ley – arable); LLA, ley (ley – arable); SEL, Lanna; UKB, Broadbalk; ESL, La Higueruela; DEB, Bad Lauchstädt; DKA, Askov; UKH, Highfield; UKW, Woburn; SiC, silty clay; SiL, silt loam; SL, sandy loam.

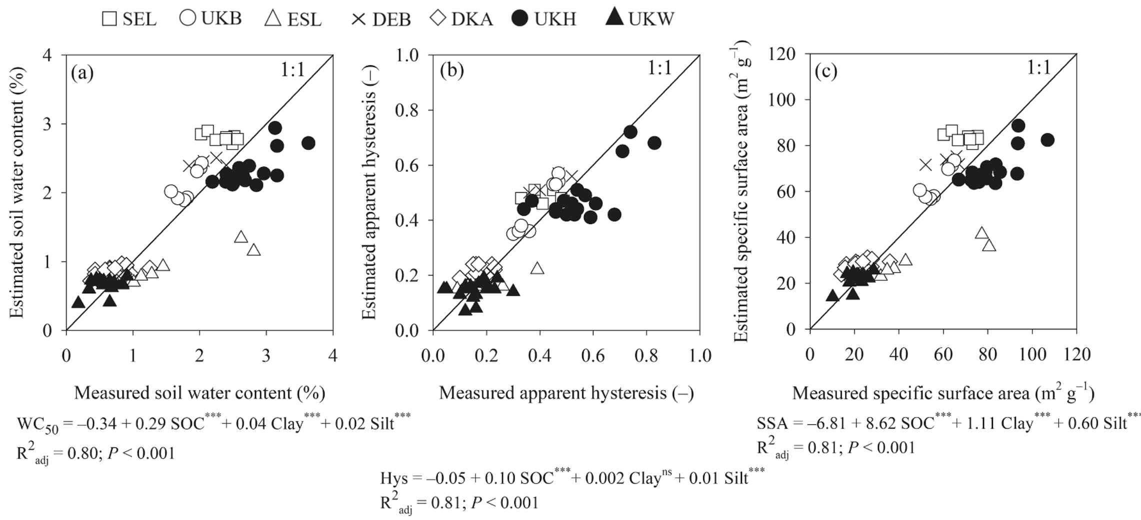

Fig. 6. Models for (a) soil water content at relative humidity of 50% (RH_{50}), (b) apparent hysteresis (Hys), and (c) soil specific surface area (SSA) based on soil organic carbon (SOC), clay and silt contents in multiple linear regression. SOC, clay and silt contents are all in %. All regressions models had an overall $P < 0.001$. *** ($P < 0.001$) and ns ($P > 0.05$) represent the statistical significance of SOC, clay, and silt in multiple linear regression, respectively. R^2_{adj}, r-squared adjusted for the number of model variables. SEL, Lanna; UKB, Broadbalk; ESL, La Higueruela; DEB, Bad Lauchstädt; DKA, Askov; UKH Highfield; UKW, Woburn.

loam DKA in wheat and barley. This phenomenon might be due to the conformational changes in the structure of SOM during the two sorption processes (Arthur et al., 2020). In general, hysteresis is expected to increase as the SOC content increases (Arthur et al., 2020) so it is unclear why the significantly increased SOC did not lead to larger hysteresis on the maize and grass in the sandy loam LTEs (Fig. 3b).

4.2. Effect of long-term cropping systems on WSIs

Long-term cropping systems are initiated to improve both soil properties and crop yield. After decades of different crop management interventions, the SOC and water sorption of the soils were affected only by the perennial grass treatment. Several possible reasons may help to explain the highest SOC content under grass treatment in silt loam UKH and sandy loam UKW LTEs. First, perennial grass had higher root biomass and longer growing seasons, which increases plant residue inputs and belowground C allocation by plants (Chen et al., 2022b). Second, harvesting biomass from crop rotation reduced a portion of plant-derived C inputs, which may limit soil C sequestration (Manevski et al., 2017). The two explanations are consistent with several other studies that showed that the SOC content is determined by the balance between plant residue that is decomposed and transformed into SOM versus the amount that is mineralized (Kallenbach et al., 2016; Chen et al., 2020a, b & 2022b). Third, the reduced soil disturbance of perennial grass rather than with crop rotation may also contribute to increasing SOC content (Carlsson et al., 2017).

Although we expected higher SOC in the ley-arable rotation, there was no difference between arable rotation and ley-arable rotation. The difference was observed between BF and croplands in the UKW site but not in the UKH site. One plausible explanation would be that the silt loam UKH site was characterized by relatively high initial SOC content, which may obscure significant changes (Table 2). Before converting to croplands, the UKH site was under perennial grass while the UKW site had been croplands for a long time. So, this land use history could also be the reason why it had high initial SOC content. This is consistent with other studies that reported that the net effects of various cropping systems on SOC content largely depend on their initial SOC content (McDaniel et al., 2014; Johnston et al., 2017; Chen et al., 2022b).

Compared to BF, permanent grass increased soil WSIs in the silt loam UKH and the sandy loam UKW sites, and arable rotation and ley-arable rotation increased soil WSIs in the sandy loam UKW site. The soil WSIs responses reflect different cropping systems-induced changes in SOC content. Since there was no significant difference in SOC among BF, WA, WLA, and LLA treatments in the silt loam UKH site, there was no significant effect on soil WSIs among the treatments.

We found that the soil WSIs in permanent grass were much higher compared with arable rotation and ley-arable rotation in the silt loam UKH site. One plausible explanation would be that permanent grass increased SOC by a larger amount compared to other treatments, which makes the soil WSIs more sensitive to changes in SOC content in the permanent grassland in both soil textures. However, we found that there was no significant difference in SOC content and soil WSIs, between arable rotation and ley-arable rotation, and between two crop types in the ley-arable rotation in both sites. Thus, although in the long-term manure application experiments, the effect of manure application seemed to depend on the crop type and soil texture, the crop type in the arable rotation and ley-arable rotation did not affect SOC content and soil WSIs regardless of the texture.

We suggest that the effects of different cropping systems on hysteresis and SSA are also caused by the changes in SOC content, because of the positive relationship between SOC and hysteresis and SSA (Arthur et al., 2018 & 2020). The higher hysteresis and SSA in grassland than the other cropping systems in the UKH site seemed to agree with our hypothesis. However, the difference in hysteresis between arable rotation and ley-arable rotation in the UKH site seemed not to agree with the trend of SOC content in the two cropping systems. Moreover, the hysteresis and SSA in the arable rotation and ley-arable rotation were not significantly different from the BF in the sandy loam UKW site, despite the significant difference in SOC content. This may be because the changes in SOC content caused by cropping management might not be enough to document significant changes in hysteresis and SSA. Thus, future studies are still required to further clarify the role of SOC content in altering soil hysteresis and SSA in sandy loams under different cropping systems LTEs.

4.3. Relationship between soil WSIs, hysteresis, SSA and SOC, clay and silt contents

The positive effects of long-term manure application on soil WSIs were consistent with the positive effects of SOC, clay, and silt contents, indicating that long-term manure application led to positive feedback to soil WSIs in a given type of soil via enhanced SOC content. The magnitude of sorbed water in the soil can be related to the contents of SOC and clay, fine silt, and clay mineralogy (Rawls et al., 2003; Arthur et al., 2015). This explanation is supported by the positive relationship between the SOC, clay, and silt contents and soil WSIs (Fig. 6a). In addition, a significant positive relationship between the SOC, clay, and silt contents and hysteresis (Fig. 6b) suggested that for soil samples with identical clay mineralogy (at a given clay content), hysteresis tends to increase with SOC content (Arthur et al., 2020). Finally, the significant positive relationship between the SOC, clay, and silt contents and SSA (Fig. 6c) suggested that SOC, clay, and silt contents may be the primary contributors to SSA, which is similar to the findings of Arthur et al. (2018). Altogether, the equations can be used to estimate the hygroscopic water content, hysteresis, and SSA of LTEs in different soil textures, crop types, and agricultural practices.

5. Conclusions

This study investigated the effect of long-term manure and different cropping systems on SOC content, soil WSIs, hysteresis, and SSA with different soil textures under different crop types. For the LTEs with manure treatments, manure application increased SOC content regardless of soil texture and crop type compared to the UNF. Due to the high clay and initial SOC content in the clayey soil, long-term manure application had no significant effect on soil WSIs, hysteresis, and SSA. However, the improvements in soil WSIs, hysteresis, and SSA in silt loam and sandy loam soils arising from manure application largely depended on the crop type. For the LTEs with different cropping systems, the rotation practice and permanent grass significantly increased SOC content compared to the BF in the sandy loam soil. Yet, there was no difference in hysteresis and SSA between the cropping systems in the sandy loam soils. On the contrary, permanent grass significantly increased SOC content, soil WSIs, hysteresis, and SSA compared to the BF in the silt loam soil, although there was no significant difference in the above-mentioned properties among the two rotation strategies and the BF. The WA treatment had significantly higher hysteresis than WLA. Across the whole dataset, we found that the soil WSIs, hysteresis, and SSA can be explained by the SOC, clay, and silt contents regardless of crop type and agricultural practices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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